THE FADING RADIO EMISSION FROM SN 1961V: EVIDENCE FOR A TYPE II PECULIAR SUPERNOVA?

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ABSTRACT

Using the Very Large Array (VLA), we have detected radio emission from the site of SN 1961V in the Sc galaxy NGC 1058. With a peak flux density of 0.063 ± 0.008 mJy/beam at 6 cm and 0.147 ± 0.026 mJy/beam at 18 cm, the source is non-thermal, with a spectral index of -0.79 ± 0.23. Within errors, this spectral index is the same value reported for previous VLA observations taken in 1984 and 1986. The radio emission at both wavelengths has decayed since the mid 1980's observations with power-law indices of $\beta_{20cm} = -0.69 \pm 0.23$ and $\beta_{6cm} = -1.75 \pm 0.16$. We discuss the radio properties of this source and compare them with those of Type II radio supernovae and luminous blue variables.

Subject headings: galaxies: individual (NGC 1058) — galaxies: general — stars: supernovae — stars: supernovae: individual (SN 1961V) — radio continuum: stars

1. Introduction

Supernova (SN) 1961V, the prototype of Zwicky's Type V SNe (now classified as either a Type II Peculiar SN or a luminous blue variable (LBV)), was unique in several respects (Branch & Greenstein 1971). Its progenitor was visible as an 18th magnitude star from 1937 to 1960. It is the first SN, prior to SN 1987A, whose parent star was identified before it exploded (assuming a SN interpretation is correct for this event). The bolometric correction, the exact distance, and the extinction are all uncertain, but its pre-outburst luminosity apparently exceeded 10^{41} ergs s^{-1}, which is the Eddington limit for a 240 $M_\odot$ star. After the explosion in late 1961, the initial peak of the optical light curve was more complex and much broader than for any supernova ever observed. Subsequently, the optical light curve decayed more slowly, by about 5 magnitudes in 8 years. Few SNe have been followed optically for more than 2 years. Optical spectra taken during this extended bright phase showed that the characteristic expansion velocity of SN 1961V was 2,000 km s^{-1}, which differs from the typical value of 10,000 km s^{-1} for most SNe. This velocity is similar to novae expansion velocities. However, no novae are this strong and none have persisted for this long in the radio. This velocity is in fact consistent with the measurements of SN 1986J (another Type II Peculiar SN), which had an expansion velocity (taken well after maximum optical brightness) of 1,000 km s^{-1} (van Gorkom *et al.* 1986, Rupen *et al.* 1987, Weiler & Sramek 1988).

Using the Very Large Array (VLA),[4] observations of SN 1961V were made in the mid 1980s, with the most definitive search in 1986 (Cowan *et al.* 1988) (hereafter referred to as CHB). CHB detected a non-thermal radio source at the precise position of SN 1961V. Fesen (1985) also reported recovering SN 1961V in the optical. CHB later detected an

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optical counterpart to SN 1961V, which was identified as an H II region using filter photometry. [CHB also detected another slightly fainter radio source to the west of SN 1961V with a similar non-thermal spectral index. This source was identified as a supernova remnant (SNR) not previously identified. This SNR also has an associated optical counterpart (i.e., an H II region).] At the distance of NGC 1058 (9.3 Mpc) (Tully 1980, Silbermann *et al.* 1996), SN 1961V is as radio luminous as the bright Galactic SNR Cas A. SN 1961V's luminosity is also comparable to several historical decades-old (also known as intermediate-age) radio supernovae (RSNe) including SNe 1923A, 1950B, 1957D, 1968D, 1970G and 1986J (Cowan *et al.* 1991, Cowan *et al.* 1994, Eck *et al.* 1998, Eck *et al.* 2000, Hyman *et al.* 1995, Weiler & Sramek 1988).

Recently, however, there has been some question about whether the event identified as SN 1961V was actually a supernova. Goodrich *et al.* (1989) suggest instead that this event was an LBV similar to η Carinae, and that the supposed supernova was an outburst of the variable star. Subsequently, Filippenko *et al.* (1995) observed SN 1961V using the Hubble Space Telescope (HST), although at that time the HST had not been refurbished. Those observations seemed to suggest a (very faint) star is still present at the site, which might or might not argue against a supernova origin. Among the brightest LBVs (e.g. η Car, P Cygni, and V 12 in NGC 2403), η Car is reported to have been the most luminous, reaching $M_{Bol} \simeq -14$. In comparison, SN 1961V was reported to have peaked at $M_{Bol} \simeq -17$ (Humphreys & Davidson 1994). This peak estimate for SN 1961V is likely underestimated by 1.2 magnitudes if one accounts for the more recently derived Cepheid distance (Silbermann *et al.* 1996). This would make SN 1961V nearly 50× brighter in the optical than η Car at maximum brightness (Humphreys & Davidson 1994).

To assess the exact nature of this event we have performed a series of observations at various wavelengths, employing the phased-VLA with the Very Large Baseline

Interferometer (VLBI) and the ROSAT X-ray satellite. In this paper we report on our recent VLA radio observations of SN 1961V and what they indicate about the nature of this event. The VLBI and ROSAT results are reported in Stockdale (2001).

2. Observations and Results

The new VLA data on SN 1961V are taken from three observing runs. In the first, SN 1961V was observed for 12 hours on 14 September 1999 at 18cm (1.67 GHz) using the VLA's most extended (A) configuration, with a maximum baseline of 34 km. These data were taken while the VLA was being used in phased-array mode for a VLBI run, and the total bandwidth was 50 MHz in each of the two orthogonal circular polarizations. The phase calibrator was J0253+3835, and both 3C286 and 3C48 were used to set the flux density scale. The total time on-source was 4.7 hours.

During the second pair of observing runs, on 21 and 25 January 2000, the VLA was in its B configuration (maximum baseline of 10km), and observed at 6cm (4.89 GHz) for a total of 12 hours. Here we used the standard VLA continuum mode, obtaining a total of 100 MHz bandwidth in each of the two orthogonal circular polarizations. The phase calibrator was J0251+4032, and 3C48 was used to set the flux density scale. In all observations the pointing center was CHB's radio position for SN 1961V, and flux densities for 3C48 and 3C286 were taken from Perley, Butler, & Zijlstra (2000).

Data were Fourier transformed and deconvolved using the CLEAN algorithm as implemented in the AIPS routine IMAGR. The data were weighted using Brigg's robustness parameter of -1, which yields a reasonably small point-spread function at the cost of a few per cent loss in sensitivity. We have also re-analyzed the CHB observations of the region, using the same data reduction procedures and inputs as were used on the current data. The results of our analyses are presented in Table 1 and Figures 1 & 2. To derive the flux density and position for SN 1961V, a JMFIT two source Gaussian fit yielded the best results for all 4 observations, while a single source Gaussian model yielded the best results for the other sources in the field of view. The positions reported in Table 1 are weighted averages of the radio positions for these sources at the various wavelengths and epochs. Uncertainties in the peak intensities are reported as the rms noise from the observations. To check that changes in measured flux densities are real, we also measured the flux density of a resolved background source present at all epochs. The background source's integrated flux densities for each wavelength band are relatively unchanged at both epochs. Our re-measurements of the CHB data are consistent, within the error bars, with those of Cowan *et al.* (1991).

3. Discussion

We have recovered a radio source at the position of SN 1961V at 18 cm and 6 cm, coincident, within the error limits, with the CHB position. Our measured flux densities at both wavelengths indicate a clear decline in the radio emissions from SN 1961V from the previous CHB observations, as indicated in Figures 1 & 2. The recently measured 18 cm flux, when scaled to 20 cm using the newly determined spectral index, indicates a reduction in the 20 cm peak flux intensity by 36% from 1984 to 1999 (see Table 1). The 6 cm peak flux intensity has also dropped by 54% in the interval from 1986 to 2000. (The western source shows no change in peak intensity for either the 6 cm or the 20 cm measurements within noise limits.) The radio emission from the vicinity of SN 1961V appears to be much more complicated than originally thought. Our new observations and re-analysis of the CHB data indicate there is at least one previously undetected radio source within $0\farcs9$ of SN 1961V. The radio emission from this source is non-thermal at both epochs and has decayed by 50% at 20 cm and by 33% at 6 cm. The region where SN 1961V is located in

NGC 1058 is clearly one of recent star formation. The peak flux density of this new source near SN 1961V is 0.040 ± 0.008 mJy/beam (at 6 cm) and 0.082 ± 0.026 mJy/beam (at 20 cm). These values are comparable to that of the distinct western source reported by CHB, so this new source may likely be a previously undetected SNR.

The decline in the radio flux density of SN 1961V is consistent with models for radio emission from SNe (Chevalier 1984). Synchrotron radiation is produced in the region of interaction between the ejected supernova shell and the circumstellar shell that originated from the prior mass loss of the progenitor star. In such models the radio emission drops as the expanding shock wave propagates outward through the surrounding and decreasingly dense circumstellar material. The decline in the flux density of SN 1961V is also consistent with Gull's (1973) model for radio emission from SNRs. This predicts an initial decline in the emission of RSNe for the first 100 years as the shock overcomes the circumstellar material and a later turn-on as the build up of material from the ISM results in an increase of synchrotron emission, as the object enters the SNR phase. Thus, the radio emission from these intermediate-age SNe, sources with ages comparable to SN 1961V, probes the transition region between fading SNe and the very youngest SNRs. In Figure 3, we illustrate the radio light curves of several intermediate-aged SNe along with a few SNRs, plotting the time since supernova explosion versus the luminosity at 20cm. It is clear that the radio emission of SN 1961V at an age of $\simeq 38$ years is very similar to known radio SNe at comparable ages, and particularly that the radio luminosities of SN 1961V, in NGC 1058, and the Type II SN 1950B, in M83, are virtually identical at similar ages.

As shown in Table 1, our new observations indicate that SN 1961V remains a non-thermal radio source. The spectral index, α, is relatively unchanged although the error bars are rather large. The spectral index was derived using the peak intensities, in order to limit the contribution from the surrounding H II region. We might expect a possible flattening of the radio spectrum as the emission from SN 1961V continues to fade. This would be an indication of the increasing contribution from the thermal emission of the associated H II region. Such was the case for the radio (Cowan *et al.* 1994) and optical (Long *et al.* 1992) emissions of SN 1957D, in M83, which has now faded below the level of an associated H II region. The current and previous values of α for SN 1961V are still consistent with spectral indices of intermediate-age RSNe at similar wavelengths, as shown in Table 2. The non-thermal nature of these sources is well-documented, as are those for young radio SNRs, with Cas A, the youngest, whose spectral index ranges from -0.92 to -0.64 (Anderson *et al.* 1991).

We can also compare the rate of decline of radio emission for SN 1961V, as measured by a power-law index ($S \propto t^{\beta}$), with decline rates of known Type II RSNe (see Figure 3). The power-law indices for SN 1961V were determined from the peak intensities to be $\beta_{20cm} = -0.69 \pm 0.23$ and $\beta_{6cm} = -1.75 \pm 0.16$. The decay indices for SN 1961V fall within a range of previously measured indices for some intermediate-age RSNe (see Table 2). In particular, SN 1957D and SN 1970G both have fairly rapid decline rates, while the younger Type II RSNe (SN 1979C and SN 1980K) indicate a slower rate of decline. We also note that while the radio emission from SN 1980K has abruptly dropped after approximately ten years (Weiler *et al.* 1992, Montes *et al.* 1998), SN 1979C (at a greater distance than SN 1980K) is still emitting at detectable levels (Weiler *et al.* 1991). Recently the radio emission of SN 1979C appears to have flattened, as indicated in Figure 3. This may be a result of the shock wave hitting a denser region of circumstellar material (Montes *et al.* 2000). The implications of these comparisons with SN 1961V are that its shock may be traveling through considerably more circumstellar material than similarly-aged RSNe, e.g., SN 1957D. As a result, its radio flux continues to drop at a slower rate more akin to the younger RSNe, i.e. SNe 1979C, 1980K, and 1986J (the only other identified Type II_{pec} SN). Consistent with this interpretation is the very rapid decline in the radio emissions of Type

Ib RSNe, e.g. SN 1983N and and SN 1984L, which presumably have less circumstellar material (see Table 2). Based on these comparisons the radio observations of SN 1961V are consistent with Type II RSNe.

Radio comparisons between η Car, the super-luminous LBV, and SN 1961V are more problematic since the first radio observations of η Car were made 100 years after its eruption. η Car, with a 20 cm flux density of 0.9 ± 0.3 Jy (Retallack 1983), is in fact not a strong radio source when compared to SN 1961V. In order to determine η Car's 20 cm flux at the current age of SN 1961V, we have naively assumed a range of potential β values for η Car from -1, our measured index for the decline of the flux at 20 cm of SN 1961V, to -3, the index for the decline of SN 1957D. Applying these constant decay rates to η Car, its 20 cm flux (40 years after outburst) would range from 5 to 65 times the Retallack (1983) measurement. This would result in η Car being at least 1,000 times weaker than the radio source at the position of SN 1961V reported in this paper. η Car's 3 cm flux was measured over a period of 5 years by Duncan, White, & Lim (1997) and found to vary between 0.5 Jy and 2.8 Jy, well below the levels of 6 cm & 20 cm emissions of SN 1961V. They further report that η Car's spectral index between 3 cm and 6 cm appears to peak at $+1.8$ at the position of η Car and then drops radially toward an index of 0. The source of the radio emission is believed to be thermal radiation from H II regions associated with η Car (Retallack 1983). The spectral index derived from radio observations at 2 cm and 6 cm of Skinner *et al.* (1998) of P Cyg, another LBV, is 0.47 ± 0.12. (P Cyg's last reported outburst was in the 17th century.) The positive values of the LBV spectral indices are obviously very different from the negative (i.e. non-thermal) indices for such events as SN 1961V, SN 1923A [the oldest RSN], and Cas A [the youngest radio SNR] (Anderson *et al.* 1991, Cowan *et al.* 1991, Eck *et al.* 1998). The non-thermal spectral indices for SNe and SNRs result from a shock front interacting with the CSM and ISM. As the referee has pointed out, it is possible that P Cyg and η Car may have been non-thermal radio sources immediately following their initial outbursts. Unfortunately there is no observational evidence to support or refute this possibility. Further, it is uncertain whether the radiation from an LBV event would remain non-thermal this long after the outburst. One of the most recent LBV events in the Small Magellenic Cloud, HD 5980, was observed in the radio by Ye, Turtle, & Kennicutt (1991) prior to LBV outbursts in 1993 and 1994. It was later observed in 1996 using the Australian Telescope Compact Array at 3 cm and 6 cm for ~ 1 hour. No compact radio emission was detected from the vicinity of the star, with an upper limit threshold of a few mJys (S. M. White 2001, private communication).

4. Conclusions

Our radio measurements have detected a source at the position of SN 1961V. The source's radio luminosity, its spectral index, and its decay index are all consistent with values reported for Type II RSNe and thus appear to support a supernova interpretation. However, the lack of radio observations of similarly-aged bright LBVs prevents a definitive identification of the true nature of SN 1961V. Additional multiwavelength observations of SN 1961V, as it evolves, will clearly be needed to make a final judgment about the nature of this enigmatic event. These should include further monitoring with VLA and using the Space Telescope Imaging Spectrograph (STIS) to analyze nebular emission lines from the region near SN 1961V to discriminate LBV ejecta nebulae ([N II]-bright), decades old SNe ([O III] and [O I]-bright), and mature SNRs ([S II]-bright). The latter observations could be very useful in ruling out one of the two scenarios for SN 1961V.

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Table 1. Radio Observations of the Region Near SN 1961V

	SN 1961V	Western Source
Right Ascension (J2000)	$02^h43^m36\overset{s}{.}46 \pm 0\overset{s}{.}02$	$02^h43^m36\overset{s}{.}24 \pm 0\overset{s}{.}01$
Declination (J2000)	$+37°20'43\overset{''}{.}2 \pm 0\overset{''}{.}2$	$+37°20'43\overset{''}{.}8 \pm 0\overset{''}{.}4$
18 cm[a](14 Sept. 1999)	0.147 ± 0.026	0.117 ± 0.026
6 cm[a](21 & 25 Jan. 2000)	0.063 ± 0.008	0.056 ± 0.008
Spectral Index[b]α^{18cm}_{6cm}	-0.79 ± 0.23	-0.64 ± 0.28
20 cm[a](15 Nov. 1984)	0.229 ± 0.020	0.160 ± 0.020
6 cm[a](13 Aug. 1986)	0.135 ± 0.013	0.070 ± 0.013
Spectral Index[b]α^{20cm}_{6cm}	-0.44 ± 0.15	-0.98 ± 0.22

[a] peak flux density (mJy/beam)

[b] $S \propto \nu^{\alpha}$

Table 2. Comparison with Radio Supernovae

Name	SN Type	Spectral Index (α)[a]	Decay Index (β)[b]
SN 1923A	II_P	-1.00 ± 0.30	-6.9 ± 4.0 (6 cm)
SN 1950B	II?	-0.45 ± 0.08	insufficient observations
SN 1957D	II?	-0.30 ± 0.02	-2.90 ± 0.07 (20 cm)
			-1.70 ± 0.04 (6 cm)
SN 1961V	II_{pec}	-0.79 ± 0.23	-0.69 ± 0.23 (20 cm)
			-1.75 ± 0.16 (6 cm)
SN 1970G	II	-0.56 ± 0.11	-1.95 ± 0.17 (20 cm)
SN 1979C	II_L	-0.72 ± 0.05	-0.71 ± 0.08 (20 cm & 6 cm)
SN 1980K	II_L	-0.50 ± 0.06	-0.65 ± 0.10 (20 cm & 6 cm)
SN 1986J	II_{pec}	-0.30 ± 0.06	$-1.18^{+.02}_{-.04}$ (20 cm & 6 cm)
SN 1983N	I_{SL}	-1.0 ± 0.2	-1.5 ± 0.3 (20 cm & 6 cm)
SN 1984L	I_{SL}	-1.03 ± 0.06	-1.59 ± 0.08 (20 cm & 6 cm)

[a] $S \propto t^{\beta}$

[b] $S \propto \nu^{\alpha}$

References. — Cowan *et al.* 1991, Cowan *et al.* 1994, Eck *et al.* 1998, Panagia *et al.* 1986, Rupen *et al.* 1987, Weiler *et al.* 1986, Weiler *et al.* 1992, Weiler *et al.* 1991

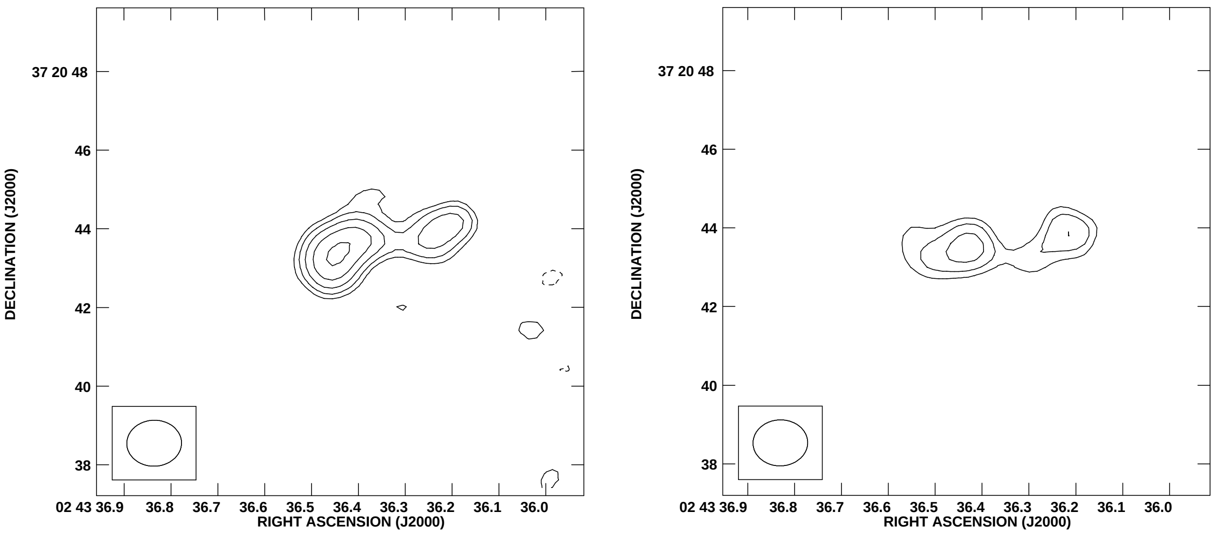

Fig. 1.— *(a.)* (left) Radio contour map at 20 cm (1.5 GHz) of SN 1961V (the strong eastern source) and a neighboring SNR (western source). Contour levels are -0.11, -0.08, -0.06, 0.06, 0.08, 0.11, 0.16, 0.23, and 0.32 mJy beam^{-1}, with a beam size of $1\farcs26 \times 1\farcs05$, p.a. $= 89°$, and rms noise of 0.026 mJy beam^{-1}. Observations taken with the VLA in A configuration 15 November 1984. *(b.)* (right) Radio contour map at 18 cm (1.7 GHz) of the same region. Contour levels are -0.11, -0.08, -0.06, 0.06, 0.08, 0.11, 0.16, 0.23, and 0.32 mJy beam^{-1}, with a beam size of $1\farcs20 \times 1\farcs01$, p.a. $= 82°$, and rms noise of 0.020 mJy beam^{-1}. Observations taken with the VLA in A configuration 14 September 1999.

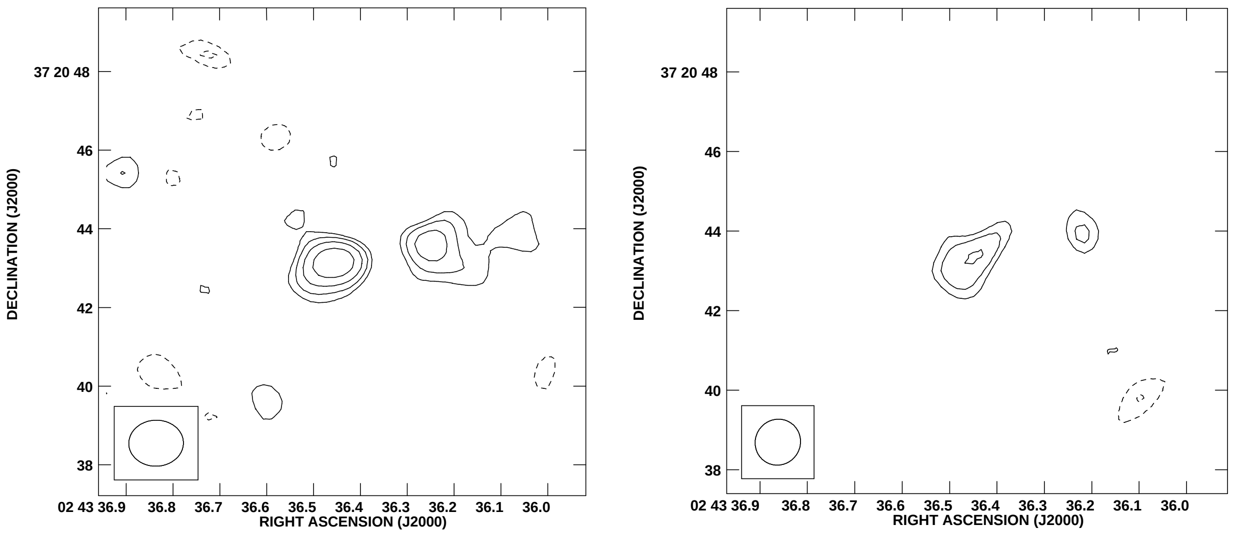

Fig. 2.— *(a.)* (left) Radio contour map at 6 cm (4.9 GHz) of SN 1961V (the strong eastern source) and a neighboring SNR (western source). Contour levels are -0.07, -0.05, -0.03, 0.03, 0.05, 0.07, 0.10, 0.14, and 0.19 mJy beam^{-1}, with a beam size of $1\farcs39 \times 1\farcs17$, p.a. $= -89°$, and rms noise of 0.013 mJy beam^{-1}. Observations taken with the VLA in B configuration 13 August 1986. *(b.)* (right) Radio contour map at 6 cm (4.9 GHz) of the same region. Contour levels are -0.07, -0.05, -0.03, 0.03, 0.05, 0.07, 0.10, 0.14, and 0.19 mJy beam^{-1}, with a beam size of $1\farcs17 \times 1\farcs13$, p.a. $= -35°$, and rms noise of 0.008 mJy beam^{-1}. Observations taken with the VLA in B configuration 21 & 25 January 2000.

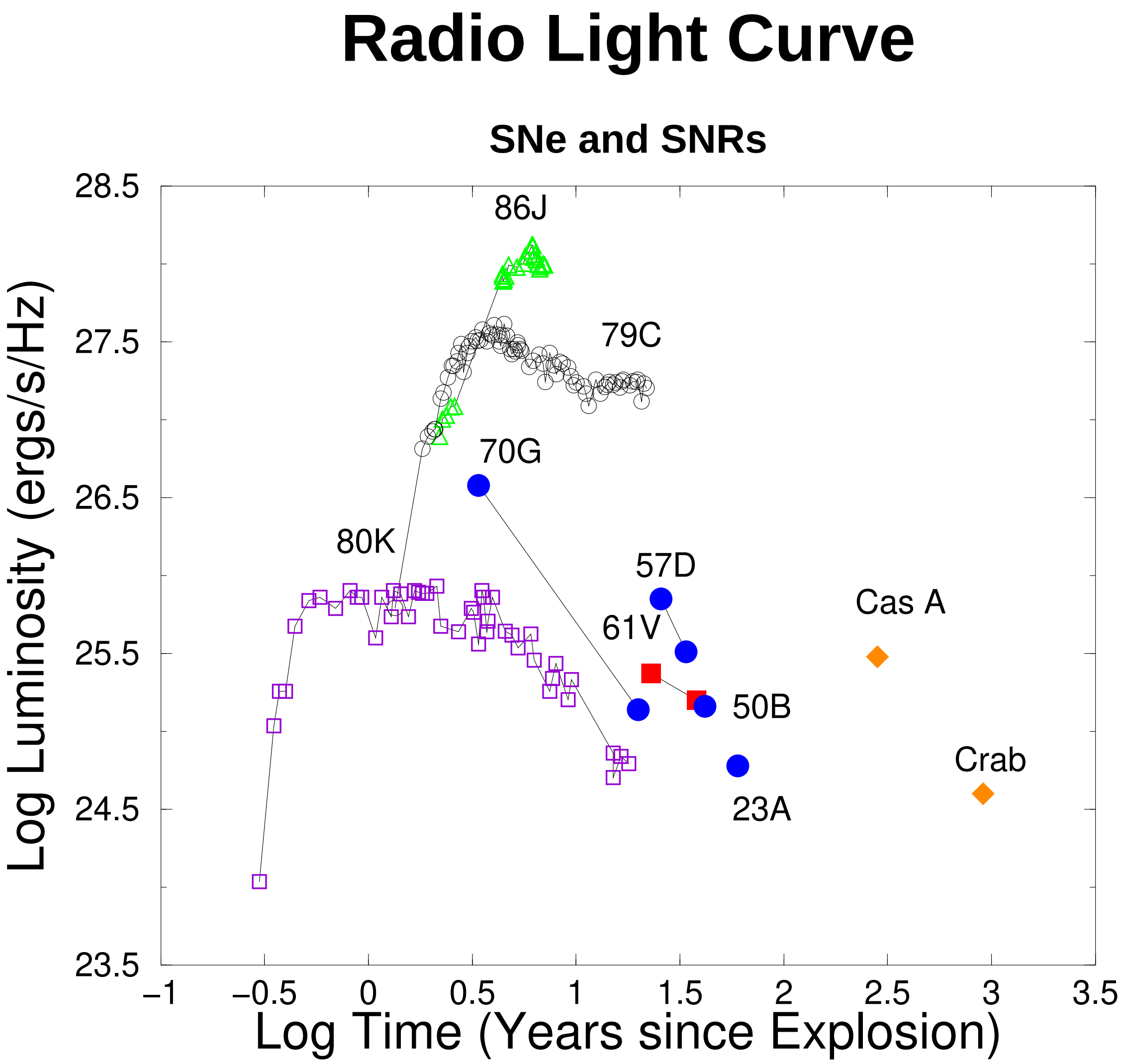

Fig. 3.— Radio light curve for SN 1961V at 20 cm compared to several RSNe and SNRs. Data, fits and distances for SN 1923A, from Eck *et al.* (1998) and Saha *et al.* (1995); for SNe 1950B & 1957D, from Cowan *et al.* (1994) and Saha *et al.* (1995); for SN 1961V, from this paper and Silbermann *et al.* (1996); for SN 1970G, from Cowan *et al.* (1991) and Kelson *et al.* (1996); for SN 1979C, from Weiler *et al.* (1986, 1991), Montes *et al.* (2000), and Ferrarese *et al.* (1996); for SN 1980K, from Weiler *et al.* (1986, 1992), Montes *et al.* (1998), and Tully (1988); and for SN 1986J, from Rupen *et al.* (1987), Weiler *et al.* (1990), and Silbermann *et al.* (1996). Luminosities for Cas A and the Crab from Eck *et al.* (1998).